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Integration and Testing of Ice-/Mixed-Phase Precipitation Models for GPM Radar-Radiometer Algorithm Applications

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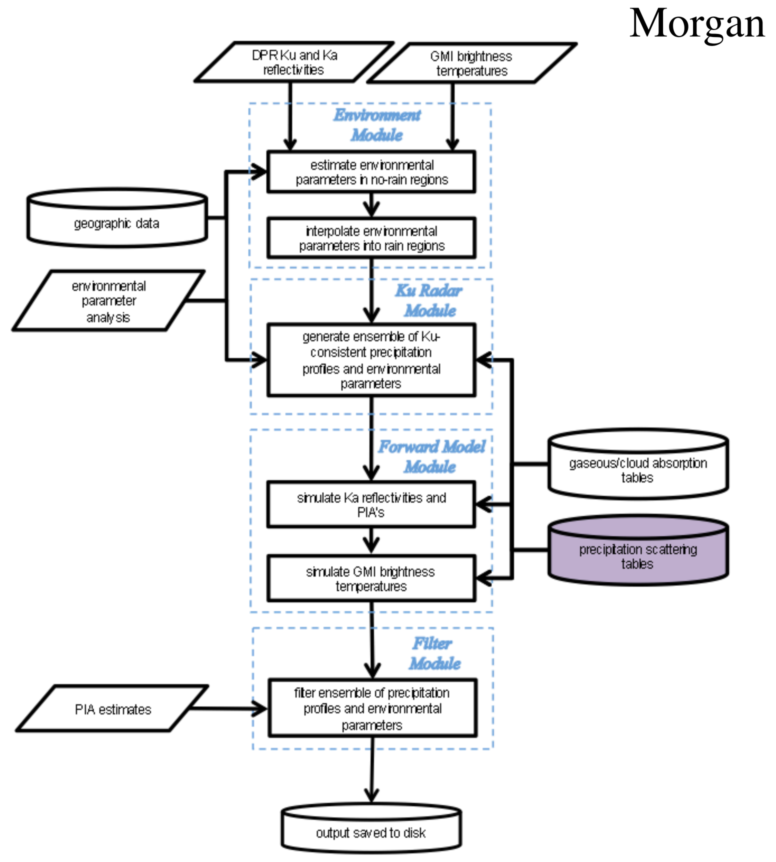


Why?

to improve the physical / statistical models used in GPM radar and combined radar-radiometer precipitation estimation algorithms. At left is a schematic of the GPM combined radar-radiometer precipitation estimation algorithm. This algorithm uses input radar reflectivities from the Dual-frequency Precipitation Radar (DPR) and microwave radiances from the GPM Microwave Imager (GMI) to deduce profiles of precipitation in all phases (liquid, ice, and mixed-phase). The accuracy of these precipitation estimates depends not only on the validity of the input data, but also on the realism and representativeness of the physically-based precipitation profile models used to fit the input data.

In the figure at left, the microwave electromagnetic scattering properties of precipitation particles are tabulated in the purple static file. These tabulated scattering properties are functions of the assumed particle phase (temperature), size distribution, density distribution (for ice and mixed-phase), habit, and meltwater fraction. In addition to the tabulated scattering properties, for algorithm applications it is also important to prescribe the statistical behavior of precipitation particle size distributions; e.g., the covariance of particle size distribution parameters as a function of altitude. In sum, the objective of this work is to develop better parameterizations of the physical and statistical properties of ice and mixed-phase precipitation for algorithm applications.

Modeling of Ice-/Mixed-Phase Precipitation in Algorithms

The particle scattering models developed during the TRMM era assumed that all precipitation-sized particles were spherical, due to the simplicity of computing the single-scattering properties of spherical particles. However, it is known that larger raindrops are better approximated by oblate spheroids, and ice-phase precipitation particles exhibit a variety of complicated particle shapes. The focus of our investigation will be to see if we can find reasonable parameterizations of ice- and mixed-phase precipitation particle size distributions and particle shapes that produce bulk scattering properties that are consistent with simultaneous radar, radiometer, and *in situ* microphysics probe observations from the GPM field campaigns.

For each particle size in any prescribed particle size distribution, the mass (or density) of the particle, its shape or habit, and the meltwater fraction of the particle must be specified. Starting with pure ice-phase precipitation, we have examined the properties of both pristine crystals (plates, needles, dendrites) as well as aggregates of crystals. Aggregate ice particles are particularly important because they tend to be the dominant particle habit among particles of relatively large size, and they also produce high radar reflectivities at the onset of melting.

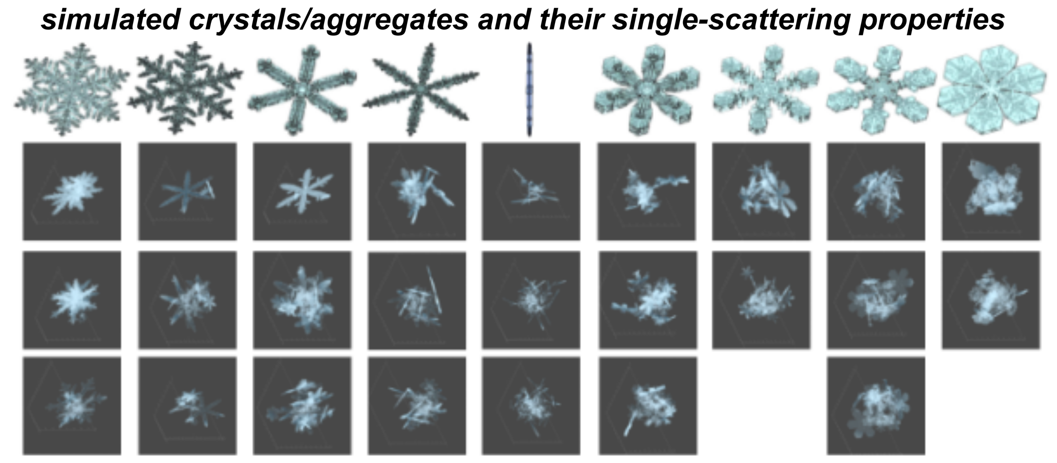
We have implemented a 3-D growth model for pristine crystals and a pseudo-gravitational collection model to create aggregate particles. The figure at above right contains images of pristine ice crystals that were simulated using the growth model, and the various aggregates shown below the crystals are constructed from crystals of the same habit but with different sizes and spatial orientations, that have been sequentially collected. The constructed particles are filtered to represent different observed mass-size relations.

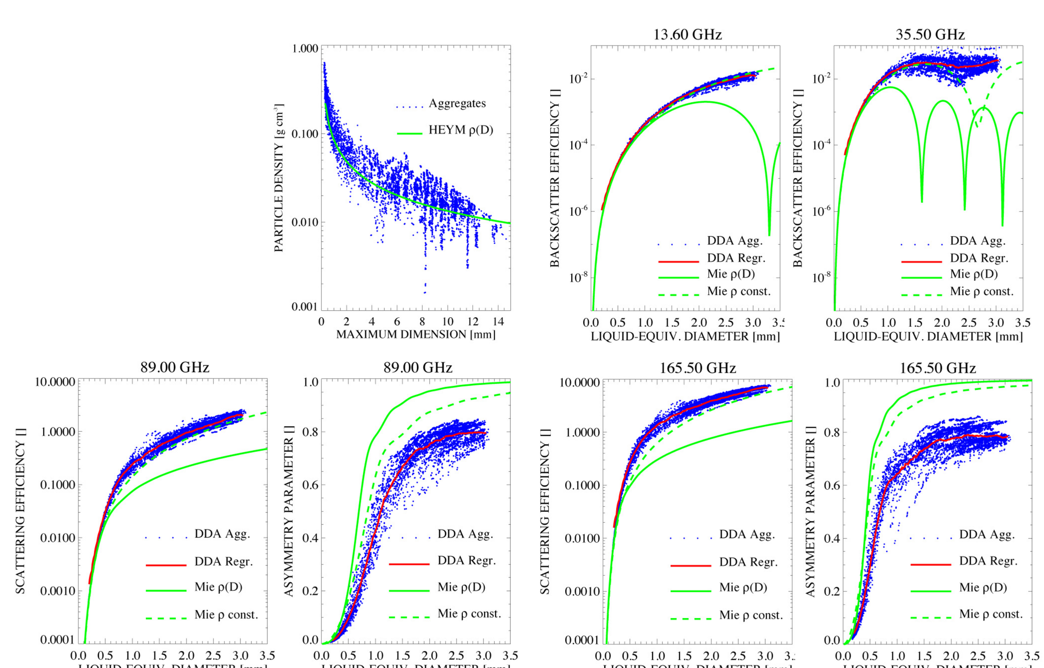
Using this method, roughly 6600 ice particles have been simulated, ranging from single pristine crystals to multi-crystal aggregates (sizes from 260 to 14,260 μm maximum dimension, although recently, particles with maximum dimensions up to ~25,000 μm have been generated). Each ice particle is constructed on a 3D numerical grid, and the microwave single-scattering properties of each particle are computed using the discrete dipole approximation (DDA; see Draine and Flatau, JOSA, 1994). In the DDA, a particle is represented by a grid of dipoles; each dipole interacts with an incoming electromagnetic wave as well as the scattered waves from all other dipoles in the particle. At above right are simulations of the single-scattering parameters of the individual particles (blue dots) using DDA, as well as the parameters for spheres of the same mass and either variable density (solid green lines) or a constant density of 0.1 g cm^{-3} (dashed green lines), derived from Mie theory.

Relative to the variable-density spheres, the constant density Mie spheres provide a better approximation to the aggregate particle backscatter efficiencies at 13.6 and 35.5 GHz. However, note that at the 89 and 165.5 GHz channel frequencies of the GMI, the asymmetry parameters of the Mie spheres are consistently higher than the aggregate asymmetry parameters. This characteristic leads to an inability of Mie spheres to simultaneously fit radar and high-frequency radiometer data in field campaign tests (see Olson et al., JAMC, 2016).

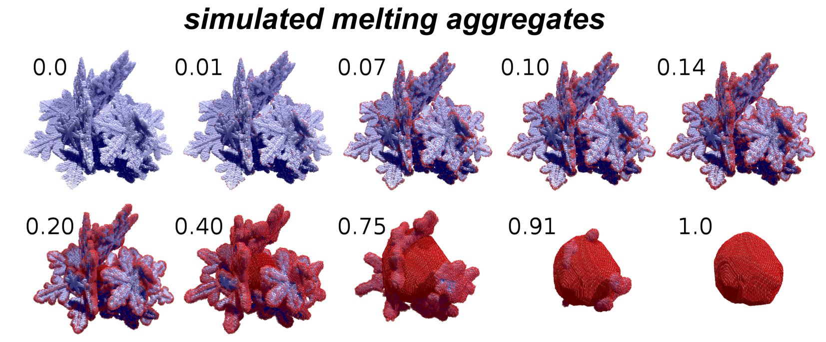
The properties of melting ice crystals, aggregates, and graupel are also being investigated. In one approach, the ice precipitation is represented on a 3D grid, and melting occurs based upon the exposure of ice to air (warming), while meltwater migrates toward local centers of mass to simulate the effects of surface tension. The evolution of a melting aggregate based upon this approach is shown at above right, with ice in blue and meltwater in red. The single-scattering properties of the melting aggregates are computed using DDA and "mapped" to spherical particles with the same mass and meltwater fraction in simplified 1D thermodynamic simulations of the melting layer. Simulations of bulk reflectivity and specific attenuation based upon polydispersions of melting particles are shown at right, for different initial median volume (liquid-equivalent) diameters. It is evident that polydispersions of melting homogeneous spheres (0.1 g cm^{-3}, solid lines) have properties that are different from those of melting nonspherical aggregates (dashed lines). The different attenuation-reflectivity relationships represented by these melting particles will impact combined radar-radiometer estimates of precipitation profiles.

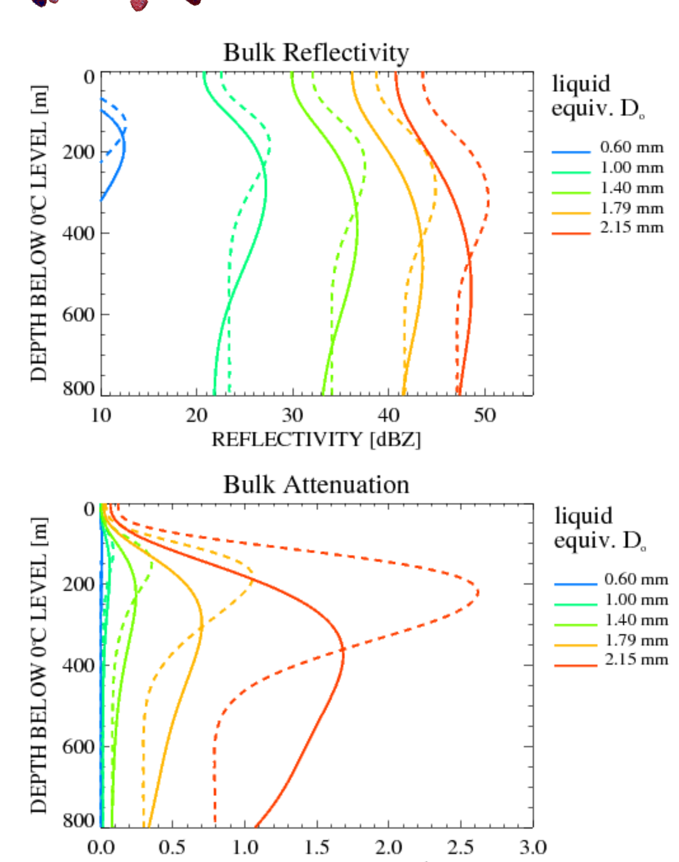
simulated crystals/aggregates and their single-scattering properties





simulated melting aggregates



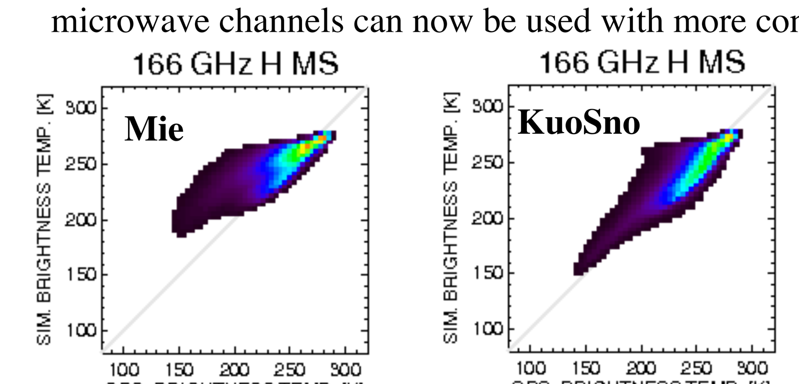


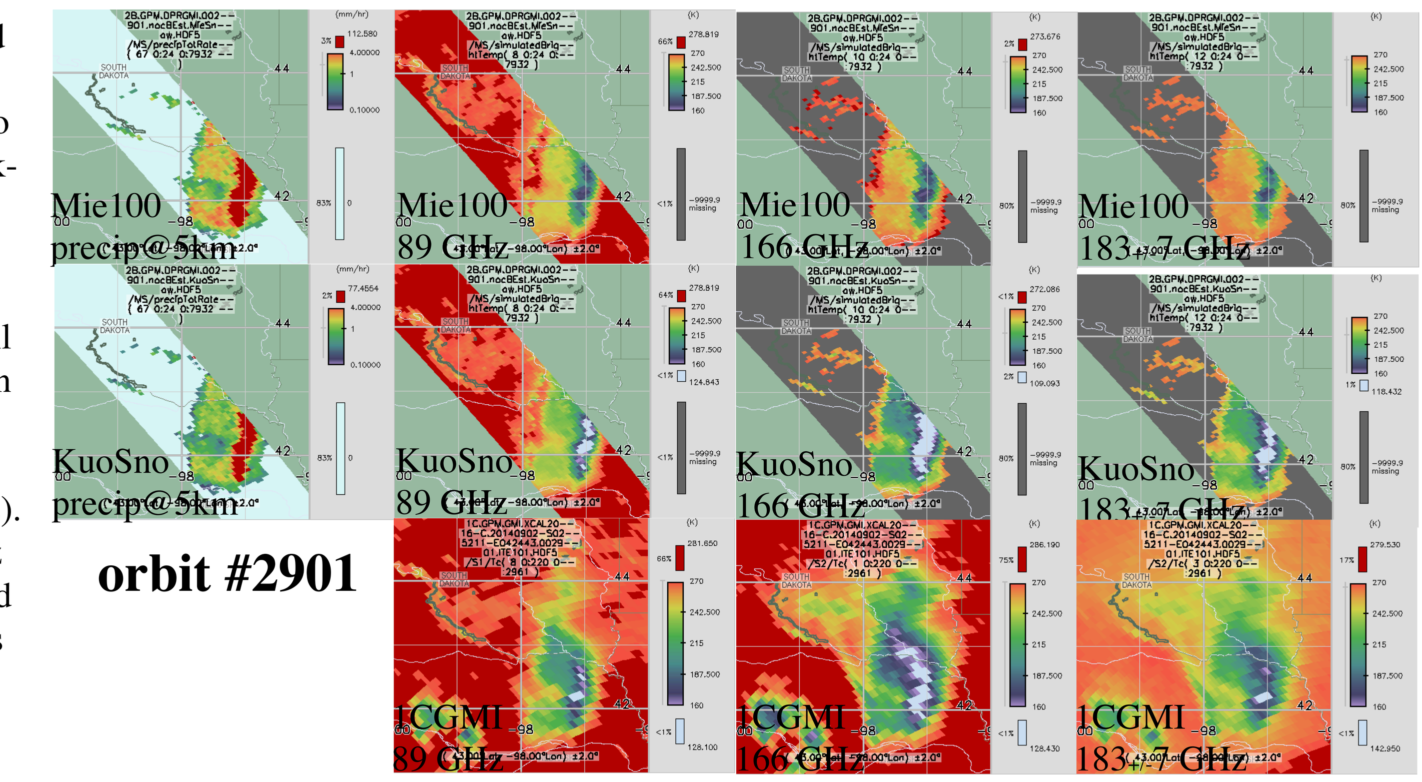
Impact of Nonspherical Ice Model on the GPM Combined Algorithm

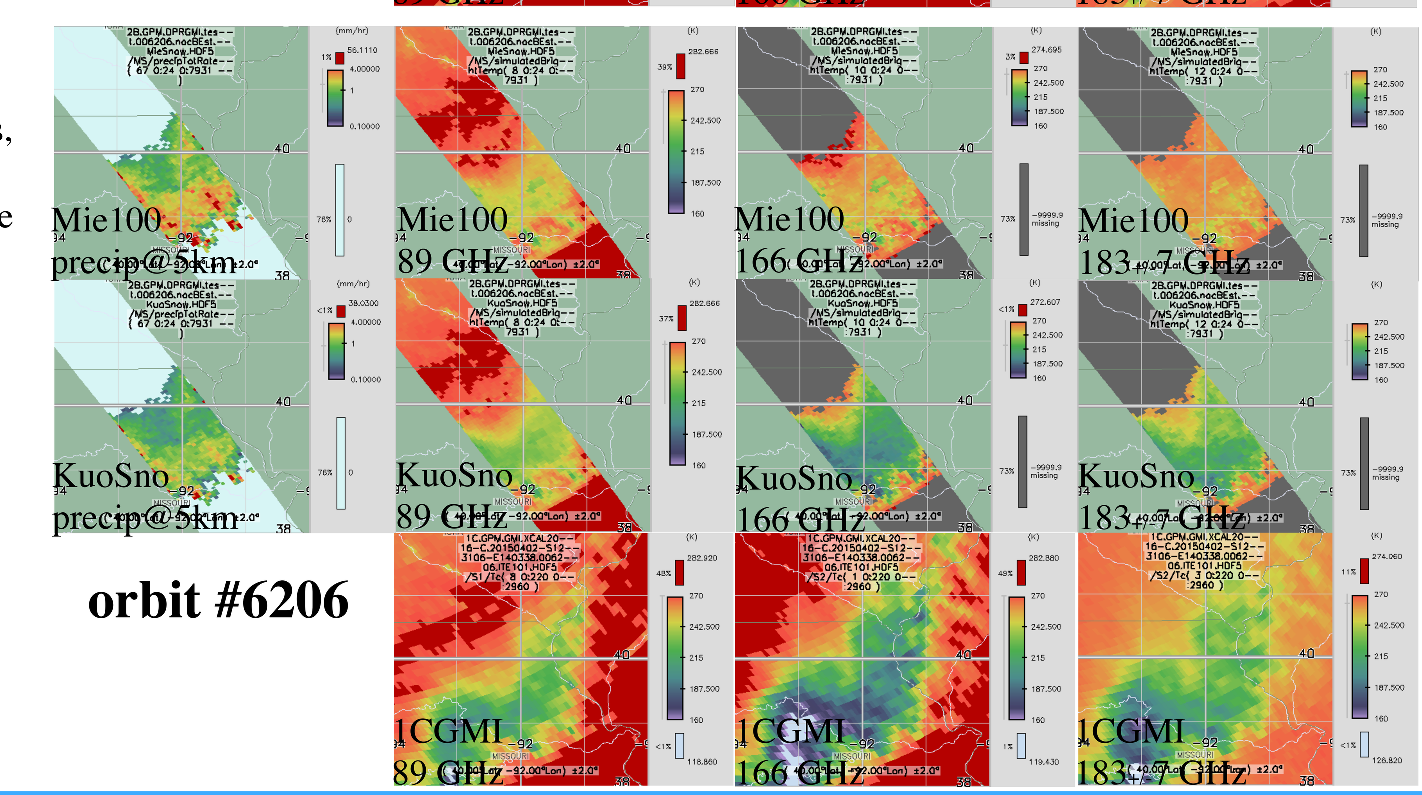
The nonspherical ice-phase precipitation model (aggregates) described at left was used to generate polydispersions of "snow" particles, and the scattering properties of these particles were integrated over assumed normalized gamma particle size distributions to obtain bulk scattering properties. These scattering properties were introduced into look-up tables that support the V05 combined radar-radiometer precipitation estimation algorithm.

GPM combined algorithm estimates of snow rates just above the freezing level, as well as simulated upwelling brightness temperatures at 89, 166, and 183±7 GHz based upon the spherical ice-particle model (Mie 100, for 0.1 g cm^{-3} constant density spheres) and the nonspherical ice particle model (KuoSno, V05) are shown, for overpasses of mesoscale convective systems on orbits #2901 (top 3 rows) and #6206 (bottom 3 rows). Also shown are the GMI observed brightness temperatures at 89, 166, and 183±7 GHz in the lowest row of each set. The introduction of nonspherical snow into the combined algorithm results in lower estimated snow rates, yet the simulated scattering signatures (brightness temperature depressions) at the higher microwave frequencies are greater, in better agreement with the GMI scattering signatures. This is primarily due to the lower asymmetry parameters of the nonspherical snow, which results in greater backscatter of low-intensity cosmic background radiances from space.

Below are 2-D histograms of simulated vs. observed 166 GHz brightness temperatures, derived from combined algorithm applications using spherical snow (at left) and nonspherical snow (at right) models, over the month of September, 2014. Note that the more realistic scattering of the nonspherical snow model results in lower simulated brightness temperatures, in agreement with GMI observations. The better fidelity of simulated brightness temperatures is important, because the higher-frequency microwave channels can now be used with more confidence in the estimation of snow rates. Also, the estimated precipitation profiles and associated brightness temperatures can now be introduced into the radiometer algorithm databases to support Bayesian estimation with less bias.



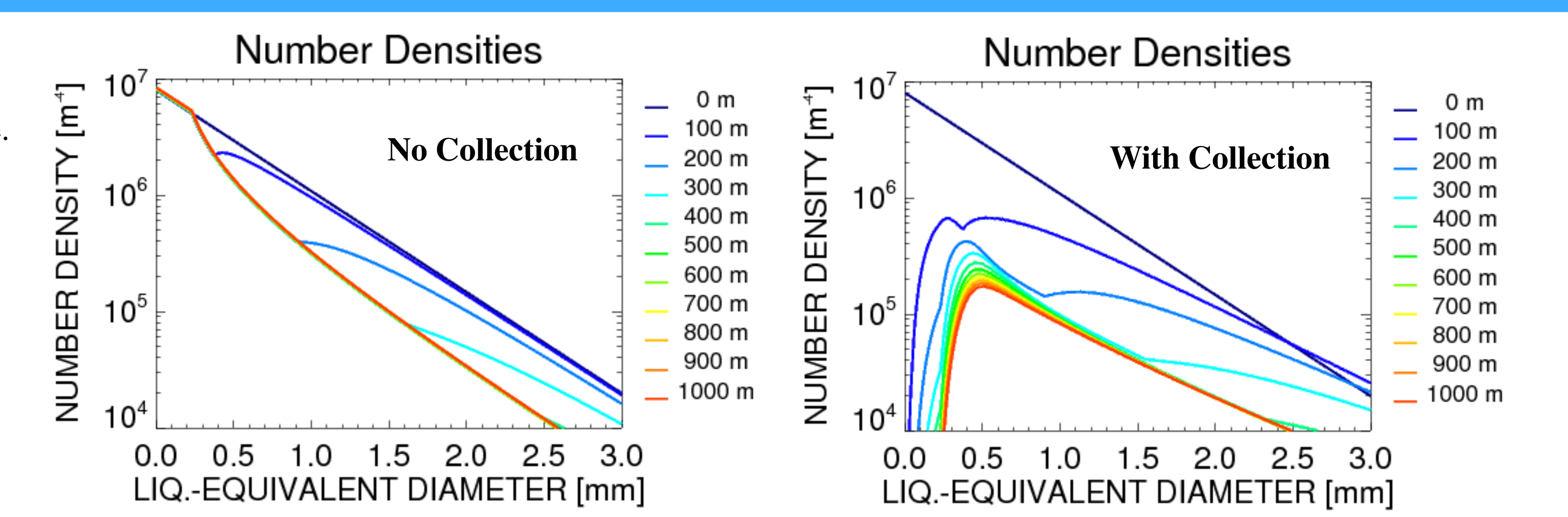


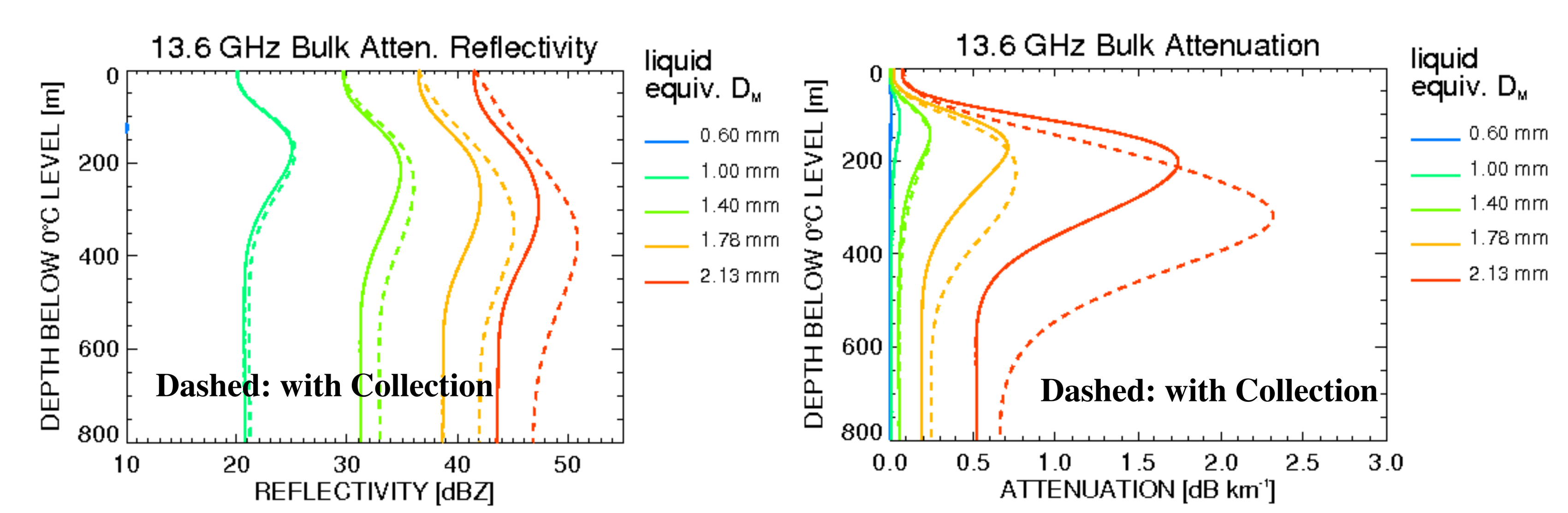


Impact of Aggregation on Melting Layer Simulations

Although nonspherical snow particles (aggregates) generally appear to provide a better model for microwave scattering characteristics, melting particles present a more difficult challenge. As described at left, the evolution of particle shape and meltwater fraction must be simulated as a function of depth below the freezing level, if melting layers in stratiform precipitation regions are to be properly modeled. The thermodynamic particle melting simulations described at left allowed each snow particle to fall, undisturbed, through the melting layer. The radar bright bands simulated using this kind of thermodynamic model tended to be weak, even though attenuation exhibited a strong peak.

To address this issue, the thermodynamic model was modified to include continuous self-collection of particles, regardless of their stage of melting. Shown in the upper panels at right are the particle number densities without (left) and with (right) self-collection. Line color indicates the depth relative to the freezing level. If self-collection is included, it can be seen that the smaller melting particles, in particular, are collected by the larger particles in the distribution, resulting in a peak number density near 0.5 mm liquid-equivalent diameter. The slope of the distribution is sub-exponential at larger particle sizes.





As described at left, the scattering properties of nonspherical aggregate melting particles are "mapped" to particles with the same mass and meltwater fraction in the thermodynamic simulations. The bulk scatter properties of the resulting particle distributions can then be calculated for initial (at freezing level) snow size distributions with different volume-weighted mean diameters (0.6, 1.0, 1.4, 1.8, and 2.1 mm). The resulting 13.6 GHz bulk attenuated reflectivity and bulk attenuation for non-collecting (solid) and collecting (dashed) particles are shown at above right. Note that due to collection, there is an increase in the size of the larger particles as they fall, which leads to a shift in the peak reflectivity and attenuation to greater depths in the melting layer. Particle self-collection leads to greater reflectivity/attenuation magnitudes as well.

A new set of melting aggregates has been created, based upon a sample of the full spectrum of nonspherical snow particles in our database. The scattering properties of these new particles will be calculated and assigned to melting particles in the thermodynamic simulations. The impact of stochastic variability on self-collection will also be investigated.